Experimental assessment of the CAM and DIS-CAM systems for the seismic upgrading of monumental masonry buildings

M. Dolce
Director of Seismic Risk Office, Dept. of Civil Protection , Rome, Italy

F. C. Ponzo, M. Di Croce, C. Moroni, F. Giordano, D. Nigro
Department of Structures, Geotechnical and Applied Geology, University of Basilicata, Potenza, Italy

R. Marnetto
TIS spa, Roma, Italy

ABSTRACT: The need of compacting masonry in its plan and improving transverse connections to get good seismic behaviours suggests the idea of using a three-dimensional tie system for the upgrading of existing masonry structures. In the CAM system (Active Confinement of Masonry), the ties are made of stainless steel ribbons. They are pre-tensioned, thus applying a light and favourable pre-compression state in masonry. Using special connection elements, it is possible to realise a continuous horizontal and vertical tie system that reduces the vulnerability of masonry, improving shear and flexural strength and ductility of masonry elements and applying an effective transverse connection between vertical layers. The paper describes the results obtained by an extensive experimental program carried out within the TREMA project on masonry elements and scaled structures made with typical materials and techniques of old masonry buildings, reinforced with the CAM system. The preliminary numerical studies of a new reinforcing system for monumental buildings realised by coupling CAM with hysteretic elements is here also presented.

INTRODUCTION

The recent Italian seismic events have shown the high vulnerability of many historical masonry buildings. Many monumental structures have been destroyed or severely damaged by even moderate earthquakes. The causes of their local or global collapse can be ascribed to the low strength of the materials, to the bad construction methodologies or to the lack of structural detailing. Many structures have been built-up with double vertical layers, without any transversal links. This particular wall geometry can often produce instability problems of the external layer under the combined action of vertical and seismic loads. Moreover, usually masonry buildings have wooden horizontal floors without any effective floor-to-walls connections.

In the past, these buildings have been repaired or retrofitted by using some conventional seismic upgrading methods, which often have been proved both ineffective and incompatible with the original structures. Hence, the interest of researchers is focalized to develop new effective upgrading systems, capable of satisfying requirements for both safety and conservation.

The new techniques shall reduce the break-up of layers and the out-of-plane wall collapse, increasing both the in-plane and out-of-plane wall strength and/or ductility.

A better structural seismic performance of masonry buildings can be obtained with effective connections between structural elements, as wall-to-wall and floor-to-wall links, able to assure a box-type behaviour.

In the recent years, the DiSGG of University of Basilicata has been working to investigate an innovative technique for masonry building retrofit: the CAM system (Active Confinement of Masonry), (Dolce et al. 2001). The strengthening system consists of insertions of special stainless steel horizontal and vertical tie ribbons, passing through transverse holes and around the masonry surface that connects and compacts masonry in its plan and improves transversal links between structural elements. The system includes also drawpieces as connection elements and angles as terminal elements. The same elements are used for special arrangements that are able to anchor horizontal floors to walls using steel ribbons loops.

The technique is highly reversible, lowly invasive and quickly applicable.

An extensive experimental investigation, aimed at validating this upgrading system, applied to masonry elements and scaled structures, has been carried out.

The performances of different masonry panels with and without CAM reinforcement have been compared through diagonal compression tests.

During the TREMA project “Technologies for the Reduction of seismic Effects on Architectural Manufactured Structures” (De Canio et al. 2000) dynamic shaking table tests have been carried on two identical 3D masonry 2:3-scale models. These buildings have been designed and constructed according to the old traditional practice of the Italian Central and Southern Apennine zone. The first model has been strengthened with the CAM system and tested to verify the effectiveness of the proposed system. The second model has been tested up to the collapse without any strengthening.

Finally, an evolution of the CAM seismic upgrading technique, called DIS-CAM (Dolce & Di Croce 2007, Dolce et al. 2007), is described. The system combines the CAM reinforcement technique, applied on slender masonry panels, with the dissipation capacity of damper devices. In this paper, the results of preliminary numerical simulations analyses carried out on a 1:6 scaled structural model of the masonry tambour of a Sicilian church retrofitted with this system are presented.

1 THE CAM SYSTEM

The CAM system belongs to the strengthening category of “horizontal and vertical ties”, as defined by recent Italian seismic codes (Ordinanza P.C.M. 3274, 2003, Ministero LL.PP, 2008). The steel ribbons can be considered as tie rods opposing to both deformation and disconnection of building elements. The ribbons are made by stainless steel, to avoid any durability problem. It is characterised by yielding and failure strengths of the order of 250÷300 and 600÷700 MPa respectively, and by more than 40% failure elongation (Dolce et al. 2008). The inelastic deformation of ribbons and the capability of the system to compacting both high degraded and cracked walls, can produce a significant increase of masonry ductility.

The application of the system requires the execution of small transverse holes in the wall, for the ribbons to pass through (Fig. 1a). The step of the holes and the number of ribbons per loop depend on the characteristics of the original masonry.

Special connection elements (Figs 1b, c) allow to realise a continuous tying system, running all along masonry walls, both horizontally and vertically (Fig. 2), to improve not only the shear resistance but also the flexural resistance of masonry walls in their single parts and as a whole.

The particular shape of the connection elements is studied in order to reduce local stresses and to mitigate damage near the ribbon contact points (corners and transverse holes).

Ribbons can also be arranged through the openings in walls or across terminal areas of the walls. The ribbon loops are closed by applying a calibrated pre-stressing tension, by means of special tools, which provide a favourable pre-compression in the masonry. Typically, the mesh arrangement can be both rectangular and triangular, having 30 ÷ 150 cm step and 1 ÷ 4 ribbons per loop.

The flexibility of the system allows several solutions to be adopted, with irregular or complex meshes. In Figure 2b, a typical arrangement on a double layer wall is shown. This particular mesh of holes, called quincunx, minimises their number and realises an efficient orthogonal mesh. The diagonal loops arrangement ensures a good connection between masonry wall and R/C floor kerb. The system can also realise a good connection between horizontal wooden floors and walls, that improves the box-type behaviour of the whole structure (Fig. 3).

Traditional metal tie-bars can be advantageously replaced by the described system by coupling a sequence of CAM ribbon loops, as shown (Fig. 4). The main advantage of this solution is that the loops can follow any irregular horizontal or vertical wall morphology.

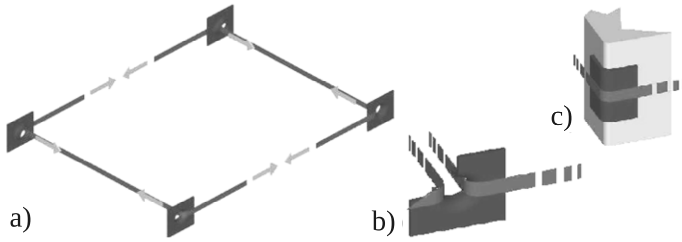

Figure 1. CAM system details: a) basic arrangement; b) connection plate; c) terminal angle plate.

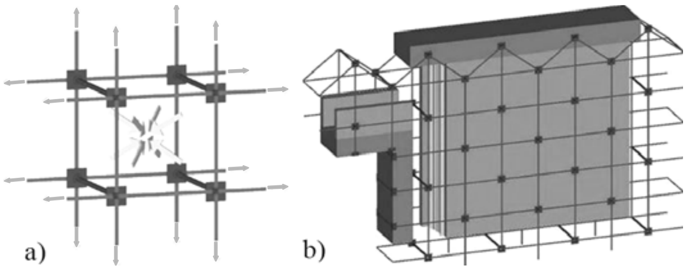

Figure 2. a) The pre-compression state applied to masonry by pre-tensioning CAM ribbons; b) arrangement in a wall with a door and a R/C upper kerb.

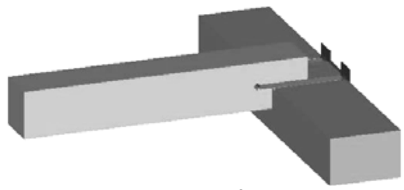
Figure 3. Connection of wooden beam with masonry wall.

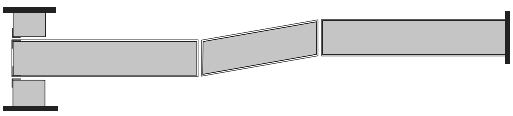
Figure 4. Coupled CAM loop ties.

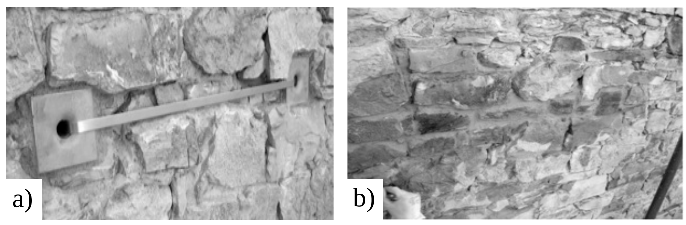

Figure 5. a) Installation of CAM system on existing masonry; b) repositioning of the cover stone material.

The CAM system is a low invasive and easily removeable technique. Stainless steel ribbons and plates can be covered with any type of mortar and plaster. Furthermore, the plaster prevents the thermal dilatation of steel ribbons. In special cases when ribbons are not covered by plaster, titanium ribbons can be used for local reinforcements.

In some cases the external ribbons and plates of the CAM system can be posed under the masonry surface after removing the superficial layer of masonry (Fig. 5a). Then the intervention can be completed by repositioning the removed stone material, as shown in Figure 5b. This solution is suitable when the external masonry surface cannot be covered by plaster (Palmieri 2008).

1.1 *Diagonal tests on brick and stuff panels*

The effectiveness of the CAM system has been previously tested through an extensive experimental program on masonry panels made with different materials and techniques of masonry buildings and strengthened with this system (Dolce et al. 2008).

More than 70 one-brick thick masonry elements, 90×90×12 cm, made of tuff stones or solid bricks, have been realised in the DISGG laboratory. The solid bricks and tuff stones used were characterized by a compressive strength respectively of 10 and 2.5 MPa. The panels have been further diversified by using cement mortar, hydraulic mortar or mix mortar respectively. The experimental program was carried out considering monotonic and cycling diagonal compression tests.

A first set of panels has been initially tested up to wide cracking condition, without any reinforcements (Figs 6a, 7a). Afterwards the panels have been recomposed and re-tested after strengthening by CAM (Figs 6b, 7b). Tests show that the CAM stops the crack separation started in the previous test and favours a crack distribution involving the entire panel, thus dissipating a large amount of energy. The average of the maximum attained displacement in the strengthened panels has been at least one order of magnitude greater than that attained in the unreinforced panels. The restoring and a slight increasing of the initial panels strengths was observed, as well as an increasing of the available ductility and of the capacity to tolerate a high number of cycles without significant strength degradation.

Further panels have been tested considering many different upgrading CAM mesh (Figs 8a, b).

The tests results have shown a significant increase of the failure strength of the strengthened panels of about +10% to +50% with respect to the unstrengthened ones (Figs 9a, b, 7a), depending on the different CAM configuration considered. The best performances of CAM were observed in less resistant panels. Almost all reinforced panels shown a deformation capacity greater than 1%, with ductility values always above 10. Among the different meshes tested, the best solution was obtained with the mesh containing both rectangular and diagonal loops (Fig. 8a).

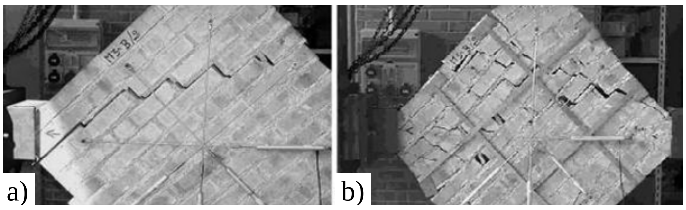

Figure 6. Diagonal compression test on a) unreinforced panel and on b) damaged panel reinforced with the CAM system.

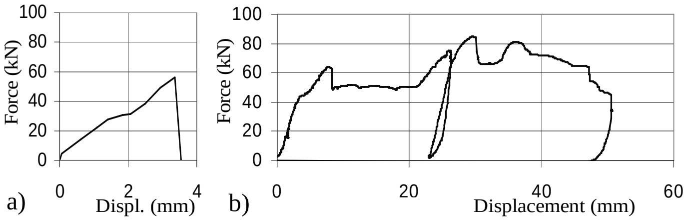

Figure 7. Force Vs Displacement of diagonal compression tests on M3B2 panel a) unreinforced (shown in Fig. 6a) and b) reinforced (shown in Fig. 6b).

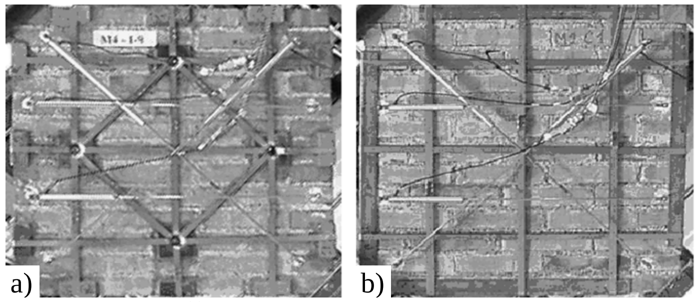

Figure 8. Two different CAM system tested meshes.

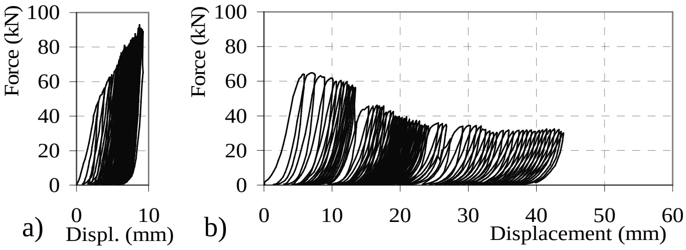

Figure 9. Force Vs Displacement diagonal compression tests on upgraded M3B1 panel on a) 2nd and b) 3rd cycling test.

1.2 *Shaking tests on 3D masonry models*

The capacity of the CAM system to prevent local and global collapses of historical masonry buildings, originally designed for gravity loads only, has been tested within an extensive experimental investigation on shaking table, carried out within the TREMA Project. The project was partially funded by the Italian Ministry for Research and coordinated by ENEA, in partnership with the Univ. of Basilicata, the Department of Civil Protection and TIS SpA.

Two identical, 2:3 scaled, 3D models (named A and B), two stories, 4.2 m tall, 3.0 m and 3.5 m wide in the X and Y directions respectively, 250 mm constant thick walls, have been realised according to the characteristics of the typical existing masonry structures of the Italian Central and Southern Apennine zone. Both models were built using masonry made by an irregular texture tuff stone and low quality mortar. The walls were composed by a double vertical layer without any transverse link. Both wall-to-wall and wall-to-floor connections were purposely realized ineffective, in order to consider an initial bad structural condition. Very flexible horizontal wooden floors were made by 2 cm thick wooden boards fixed to 10×18 cm wooden beams, while door and window openings had wooden lintels. The basement of structure was made of 40×30 cm R/C beams.

The overall weight of the building was 201.32 kN, including the masonry walls (169 kN), R/C basement (28.24 kN) and wooden elements (4.08 kN) contributions. 25 kN additional masses were placed at the floor and roof levels, in order to fulfil the similitude scaling laws.

Both destructive and non-destructive tests were preliminarily carried out on the masonry materials of the models. Several mortar samples were tested under both flexure and compression. The specimens showed a tensile and compression strength of 0.14 and 0.72 MPa respectively. The low characteristics of mortar were confirmed by penetration tests carried out on the mortar joints of the experimental models. The tuff stone characteristics were verified through compression tests, that returned compression strength equal to about 8.7 MPa.

Three masonry panels were realised considering the same technique and materials adopted for the experimental 3D models. Their characteristics were investigated through diagonal compression tests carried out considering different vertical pre-loading levels (q). The panels were initially tested up to achieving cracking condition without any reinforcements (Fig. 10a). The same panels where then recomposed and strengthened with the CAM system and re-tested (Fig. 10b). Figure 11 shows the diagonal force vs. horizontal and vertical displacements behaviour provided by the test on the unreinforced and reinforced MT-1 panel, while table 1 summarises the shear resistance outcomes of the diagonal compression test.

The first experimental model (A) was strengthened by the CAM system, consisting of stainless steel tie ribbons 350 mm spaced in both horizontal and vertical direction. The ribbons had a 19×0.75mm cross section and were installed in a single loop, in order to respect the scaling laws (a double loop with a 50×50cm mesh would be used in a 1:1 scale structure). The loops were closed by applying pre-stressing force of approximately 5 kN. Vertical links between the basement and the masonry were disposed, and no link between floors and walls.

The model B was tested without any reinforcement. Both models are shown in figures 12a, b.

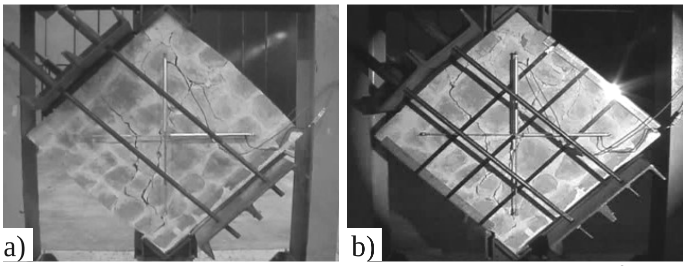

Figure 10. Diagonal compression test on a) Not Reinforced MT-1 panel; b) Reinforced MT-1 panel.

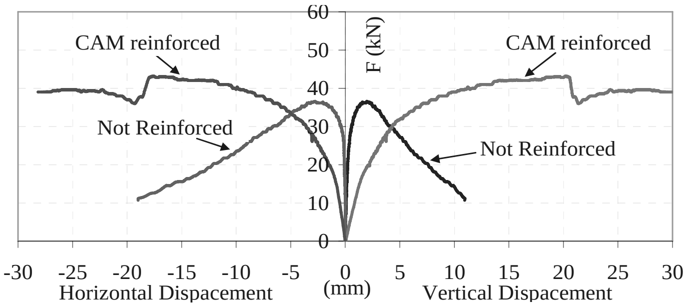

Figure 11. Diagonal Force Vs Vertical and Horizontal displacements on Not Reinforced and Reinforced MT-1 panel.

Table 1. Diagonal compression tests on masonry panels.

Panels		Unreinforced panels			Reinforced panels		
	q^*	F_{max}	d_{Fmax}	d_u^{**}	F_{max}	d_{Fmax}	d_u
	MPa	kN	mm	mm	kN	mm	mm
MT-1	0.10	37.1	2.0	11.0	43.6	20.2	30.6
MT-2	0.15	27.8	0.5	7.8	***		
MT-3	0.20	51.5	1.9	3.4	50.5	3.0	6.9

* Vertical Compression applied only on 42 × 25 cm of panel.
** Maximum vertical displacement of test.
*** Panel destroyed after Not Reinforced test.

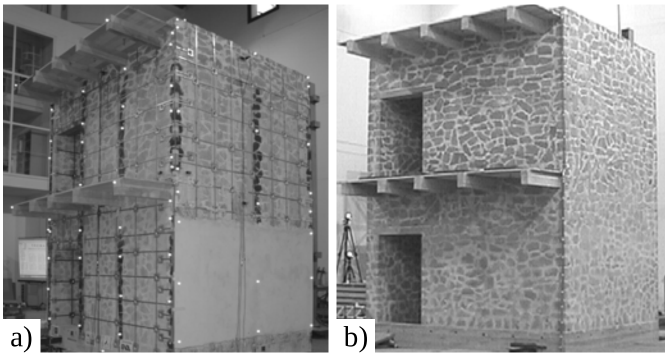

Figure 12. a) Model A with CAM system; b) Unreinforced Model B.

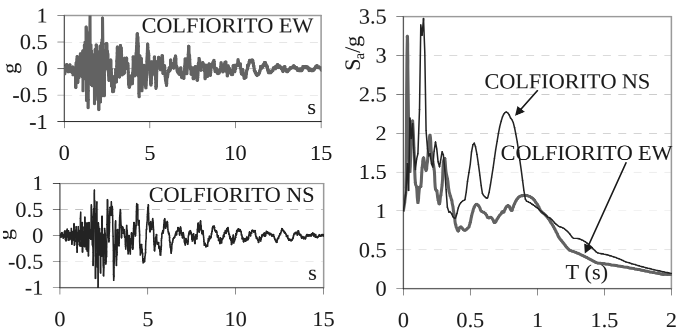

Figure 13. Colfiorito scaled accelerograms and corresponding 5% damping response spectra.

The experimental program was realised through dynamic tests carried out on the 4×4 m shaking table facility of Enea-Casaccia (Rome). The dynamic behaviour of the models was monitored through an integrated acquisition system provided by the partners (Dolce et al. 2008). Dynamic shaking table tests were carried out by applying both NS and EW component of a natural input (the 1997 Colfiorito earthquake – Fig. 13) with increasing intensity. In addition, random tests were performed before dynamic tests in order to verify model frequency decay and damage propagation in structural elements.

The test sequence of the CAM strengthened model began with the application of a low intensity random signal in order to identify the dynamic properties of the structure. The earthquake was then applied starting from 0.096g NPA (Normalized Peak ground Acceleration). NPA has been evaluated through the Housner integral of the shaking table acceleration, because it was affected by some high frequency noise (Dolce et al. 2006). The input intensity was further increased up to 1.12g NPA. At the end of the testing session, some damage was observed in two walls of the 1st floor and of the 2nd floor in the upper part of the corners, but the model was still able to carry the vertical loads.

For the unreinforced model (B) the testing sequence began again with the application of a low intensity random signal. The Colfiorito earthquake record was then applied, starting with a 0.043g NPA. The NPA was increased up to 0.34g. The first partial collapse of the model occurred at 0.24g NPA in the Y direction (Fig. 14b). Some damage in the upper parts of the corners as well as the activation of an out-of-plane collapse mechanism due to a complete disconnection of the walls, without compromising the vertical load capacity of the structure, were observed. Two more tests were then performed in order to assess the building residual strength capacity. The first test yielded the simultaneous collapse of three walls at the second floor at 0.31g NPA in the Y direction (Fig. 14c), while the second test was performed in order to achieve the total structural collapse (Fig. 14d). The damage of models are also shown by Figures 15a, b, that show the frequency decay of the experimental model registered during the dynamic tests. The higher frequency observed for Model A in both horizontal directions can be justified by the CAM contribute and by a previous damage suffered by the model B before test starting. It is also interesting to note that in the tests with CAM the 1st frequency decay in both horizontal directions, occurs in the range 0.15g÷0.55g NPA, corresponding to the activation of all cracking mechanism in the masonry. After that, any increase of input signal intensity in both directions has not produced further decays, because of the strengthening action of the CAM system. The effectiveness of the CAM system is also proved by the improvement of connections between different structural elements, such as orthogonal walls, masonry and bottom kerb, that prevents out of plane mechanisms.

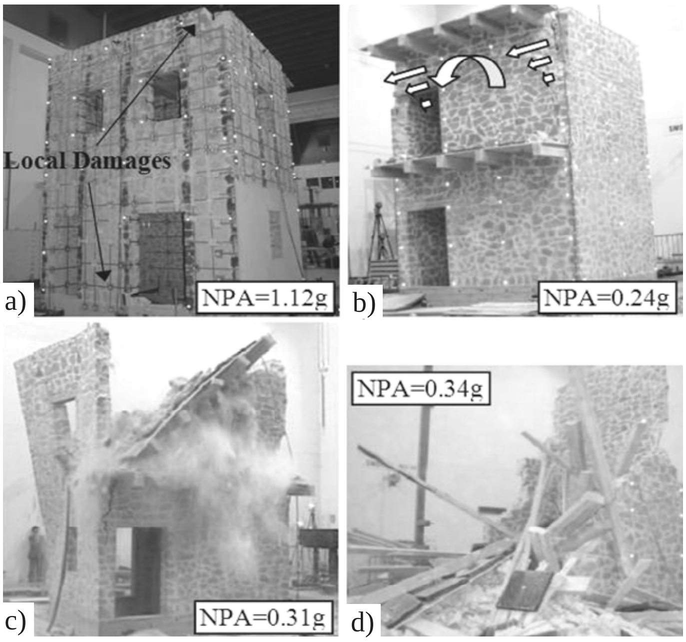

Figure 14. a) Damage suffered by Model A; b), c), d) damage and collapse sequence for Model B.

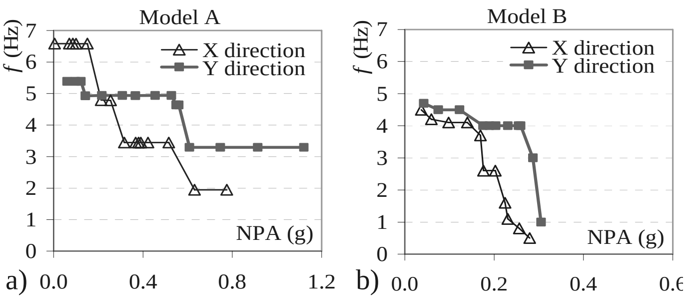

Figure 15. 1st structural frequency decay in both horizontal directions for a) Model (A) and b) Model (B).

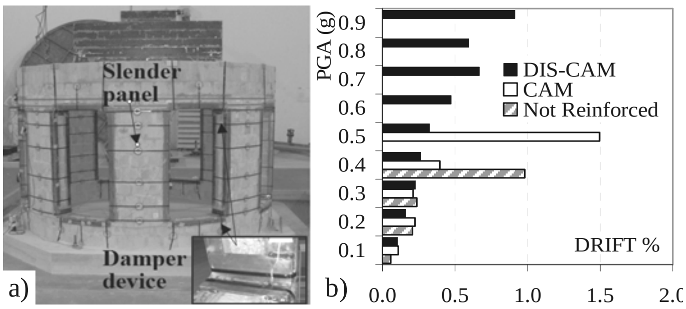

Figure 16. a) Tambour experimental model retrofitted with the DIS-CAM system; b) numerical drift for different model configurations.

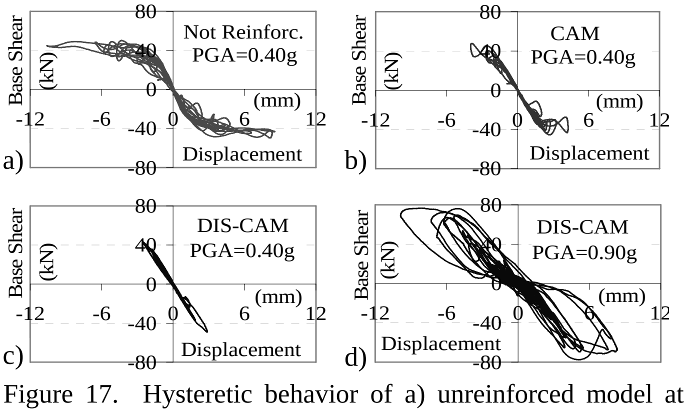

Figure 17. Hysteretic behavior of a) unreinforced model at 0.40g PGA, b) reinforced by CAM at 0.40g PGA, c) by DIS-CAM at 0.40g PGA; d) by DIS-CAM at 0.90g PGA.

2 THE DIS-CAM SYSTEM

The DIS-CAM system is a further development of the CAM system that can be usefully considered for the seismic upgrading for masonry monumental buildings. It is based on a rocking-damper system, in which the re-centring capacity is provided by the behaviour of masonry slender panels, while the dissipation capacity is mainly relied upon hysteretic steel elements stressed in flexure beyond their elastic limit. The effectiveness of the system in drastically reducing seismic displacements will be verified through an extensive experimental shaking table test program on a 1:6 scaled masonry model, reproducing the tambour of the S. Nicolò's church in Catania (Fig. 16a). The model, having circular shape, 2900 mm external diameter and 180 mm constant thick walls, has been built with squared tuff stone and lime mortar. The structure is characterised by a high vulnerability because of the presence of 8 slender panels (1080 mm high, 534 mm wide) and 8 large openings. A R/C plate, simulating the Sorbino dome, has been positioned on top of the tambour. Additional masses (89 kN) have been added on the R/C plate, in order to respect the similitude laws.

The upgrading system has been realized by applying angle steel plates and steel ribbons all around the openings in the masonry. The confinement effect due to the CAM system and the energy dissipation provided by special shaped dampers welded to the angle plate in correspondence of the corners (Fig. 16a) assure a favourable increase of the masonry strength and a considerable reduction of displacements. This particular configuration realizes a rocking-damper system.

Preliminary numerical analyses of the structure, without any reinforcement and with retrofitting systems based on the CAM system only applied to slender panels, and on the complete DIS-CAM system have been carried out. The simulations were performed using both horizontal components of the Colfiorito record, scaled in time, starting from 0.1 g PGA and gradually increasing the base acceleration up to the model collapse. Figure 16b shows the numerical drift vs. PGA for the different configurations considered in the analyses. The DIS-CAM system shows the good retrofitting capability in terms of drift reduction, allowing for PGA about twice than other analysed solutions. This effect is mainly due to the high dissipating capacity of the DIS-CAM, more evident for high PGA, as shown by Figure 17.

3 CONCLUSIONS

The effectiveness of a new seismic strengthening system, applicable to historical masonry buildings, has been tested on masonry elements and on 3D experimental models made with typical materials and techniques of old buildings. Several tests carried out on masonry panels have shown the capacity of the CAM system to improve strength and ductility of weak masonry elements. Two identical 3D masonry models have been tested by increasing the intensity of natural earthquake records. The first model (A) was tested after seismic strengthening by the CAM system; the second model was tested without any strengthening, in order to compare the effectiveness of the considered innovative technique. The model (A) was tested up to 1.12g NPA, suffering only light damage levels. The tests showed that the CAM strengthened structure is about four times stronger than the unreinforced model, due to the capability of the CAM system to insure a box-type behaviour in a model lacking of structural detailing.

The CAM system, combined with the energy dissipation capacity of particular steel dampers and with the re-centring capability of the slender masonry panels, could be very effective in upgrading some particular structures, like the church tambours herein described. The numerical study carried out in order to prepare the experimental tests on the DIS-CAM system shows that the system is very effective in limiting the seismic drift and in strengthening the considered structure, reaching as large a resistance as twice than the resistance obtained by a simple CAM solution.

4 ACKNOWLEDGEMENTS

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